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WIND EROSION AND PM_{10} EMISSIONS FROM AGRICULTURAL FIELDS ON THE COLUMBIA PLATEAU

LARRY D. STETLER

Biological Systems Engineering, Washington State University, Pullman, WA 99164-6120, U.S.A.

AND

KEITH E. SAXTON

U.S. Dept of Agriculture/Agricultural Research Service, Washington State University, Pullman, WA 99164-6120, U.S.A.

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ABSTRACT

Research to investigate relations between simultaneous processes of soil erosion by wind and PM_{10} emissions from dry land fields on the Columbia Plateau, Washington, has been initiated by the U.S. Department of Agriculture – Agricultural Research Service (ARS) and Washington State University. Dry land agriculture is the primary cropping system worldwide but is constantly threatened by erosive winds which reduce the soil resource and/or remove fines which are the most active soil portion for plant production. Soils on the Columbia Plateau are very fine-grained containing more than 4 per cent of freely occurring aggregates or particles less than 10 μm aerodynamic diameter. Analysis from eight wind events show that significant relations exist between total mass of soil in both horizontal (saltation) and vertical (suspension) transport. The data suggest that by limiting horizontal soil erosion, emitted dust can be simultaneously reduced. Aggressive conservation tillage can be an effective weapon in reducing soil erosion by maintaining surface residue and roughness.

KEY WORDS soil erosion; PM_{10} emissions; dry land farming; Columbia Plateau

INTRODUCTION

Erosion of soil from dry land regions in the United States has been a problem for centuries. Reports sent to President Jefferson by Lewis and Clark about the Columbia Plateau documented observable health-related effects on the local peoples due to atmospheric dust and state: 'soar eyes seem to be a universal complaint among these people; I have no doubt but the fine sand of these plains and rivers contribute much to this disorder' (Lewis and Clark Expedition, 1806). More than 100 years later, accounts from the 'dust bowl' era of the mid 1930s reflected that erosion of soils by wind degraded soil quality and presented a serious health hazard to people and animals alike (Kansas State Board of Agriculture, 1948).

The potential for wind erosion of soil is highest in arid and semiarid regions. Over much of the southern Great Plains region, semiarid conditions lead to maximum dust production during the spring (Gillette and Hanson, 1989). This is primarily a result of high spring winds, low rainfall and minimal vegetative cover on generally sandy soils. Climatically, the Columbia Plateau is semiarid to arid but spring rains and low winds seldom generate excessive erosion conditions. However, during the fall, timing of the highest winds of the year correlates with the planting of the winter wheat crop into very dry, pulverized silt loam soils. As a result, large areas of recently seeded land lie unprotected and highly susceptible to severe wind erosion. In dry years, erosion rates can increase by up to a factor of six over those rates measured during humid years (Gregory, 1991). These high erosion rates can be reduced somewhat by using conservation tillage practices which

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increase surface roughness and soil moisture retention (Fryrear, 1984; Hagen *et al.*, 1988; Gregory, 1991; Hagen and Armbrust, 1992). However, tilling dry soils (particularly those with low clay content) promotes weakened soil structure and reduces or eliminates surface residue.

Undisturbed soils do not naturally contain a high percentage of particles $\leq 50\,\mu m$ diameter as separate, loosely occurring grains. Instead, these finer particles often adhere to each other through chemical and electrical properties and form relatively stable aggregates. As such, grains of fine silt ($<20\,\mu m$) and clay ($<4\,\mu m$) (Pettijohn *et al.*, 1987) are not readily available to aeolian processes. During a wind erosion event, however, larger particles ($>100\,\mu m$) moving primarily by saltation can impact the surface with enough energy to cause ejection of additional saltating grains and of individual silt and clay particles as aggregates are abraded. In the absence of saltation, mechanical energy (tillage operations) can be effective in disaggregating dry soils, producing surfaces that potentially contain high percentages of loose grains. During subsequent wind erosion events, these dry, tilled soils are often highly susceptible to severe erosion, soil loss, and PM_{10} emissions. The silt loam soils on the Columbia Plateau frequently fall into the latter category.

As both farm and range lands are eroded by wind, the finer soil particles that are emitted may become suspended in the atmosphere. Recently, suspended particles $<10\,\mu m$ diameter (PM_{10}) have received attention because of increasingly identifiable health risks. The 1990 Clean Air Act (U.S. – Environmental Protection Agency (EPA), 1990) established 'acceptable' PM_{10} levels for the U.S. that should not exceed a 24-h-average of $150\,\mu g\,m^{-3}$ more than three times per year and maximum long-term exposure that should be less than $50\,\mu g\,m^{-3}$ averaged over one year. Both Spokane and Kennewick (Tri-Cities), WA (Figure 1), have been, or may soon be, classified as moderate non-attainment cities because of high concentrations of PM_{10} particulate (Stuart, 1992). In both instances, agricultural dust has had a significant impact on these status ratings, although it is not the only particulate source. Kennewick has also recorded one of the highest PM_{10} levels in the U.S. at $1689\,\mu g\,m^{-3}$ which was attributed to upwind agricultural wind erosion (D. Lauer, pers. comm., 1994).

As demands for food and fibre increase world-wide, the farmer in the U.S. is increasingly required to minimize production costs and maximize crop yields while simultaneously maintaining some measure of erosion compliance. Depending on region and soil type, conservation tillage practices can help to reduce production costs by improving crop yields through maximizing crop water utilization and reducing or eliminating water competition from weeds. In dry land farming regions such as the Columbia Plateau, these requirements

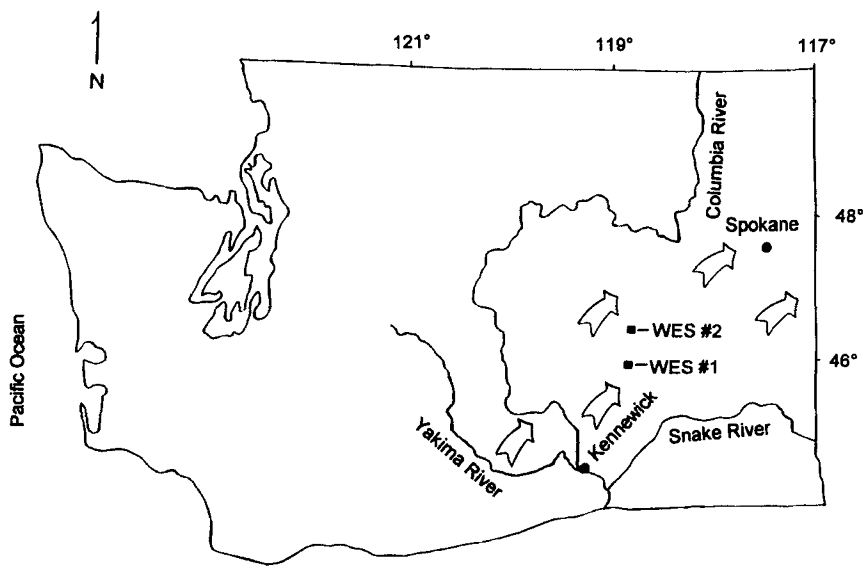

Figure 1. Physiographic map showing the locations of the wind erosion sites. Arrows show the predominant flow direction of the most erosive winds

often result in a bare, smooth soil surface that is highly susceptible to wind erosion until timely and effective management practices are implemented and/or a crop cover is established.

DRY LAND FARMING SYSTEMS

The primary crop across the dry land areas of the Columbia Plateau, where annual precipitation levels range from 200 to 356 mm, is winter wheat. Growing an economical wheat crop requires prudent utilization of available moisture. This has been achieved historically using a 2-year cropping cycle where the land lies fallow in alternate years. About 60 to 75 per cent of the region's annual precipitation occurs between November and March. Consequently, soil water storage during this period is critical to make effective use of the annual precipitation for crop production. Thus, the fallow year is generally the most important in terms of water storage and erosion control, which can be maximized by retaining residue on the surface and increasing surface roughness.

Surface residue and roughness effects

Research has shown that soil erosion decreases exponentially as a function of surface residue cover (Chepil, 1944; Siddoway *et al.*, 1965; Fryrear, 1985) (Figure 2A). The effect is largest where residue cover increases from 0 to about 30 per cent while the surface cover factor (which approximates erosion potential) decreases from 1·0 to 0·2. This is equivalent to an 80 per cent reduction in erosion potential. Above 30 per cent surface cover, additional benefits continue to decrease. Residue is most affected by the type and timing of primary tillage after autumn harvest, such as autumn chiseling which minimizes surface residue burial and creates significant roughness.

Surface roughness does not have as large an effect on soil erosion as does residue cover. Figure 2B shows that soil erosion potential (plotted as a surface roughness factor) decreases as a nearly linear function of

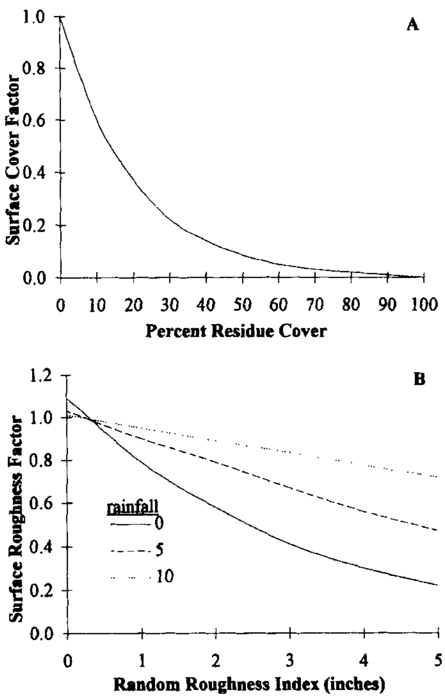

Figure 2. Surface cover (A) and surface roughness (B) effectiveness factors for erosion control in the inland northwest. The surface cover and roughness factors approximate the proportionate reduction in soil erosion from highest (factor of 1) to lowest (factor of 0) for each percentage and incremental increase in residue cover and roughness (with effects due to precipitation), respectively (data from McCool, ARS, Pullman, WA)

roughness (measured as the standard deviation of the difference between the average height of roughness elements and the mean soil surface) and becomes less with higher precipitation. Roughness elements are important in that they slow surface water movement and promote increased infiltration, thereby reducing runoff and soil erosion by water. Roughness also acts as an important trapping mechanism for saltating particles which effectively reduces the rate of soil erosion and emissions of fine dust.

Fallow and climatic interactions

Fields harvested in autumn are generally tilled with operations that protect the soil from erosion losses during the winter. In spring (around May), these fields begin to be prepared for autumn seeding by 'sealing-in' winter moisture using a rod-weeder. This implement packs the ground below 100–150 mm and creates a 'dust mulch' on the surface up to 150 mm thick. This dust mulch consists of disaggregated soil, clods and residue and effectively eliminates soil moisture losses due to capillary action. Subsequent tillages are performed as required to kill weeds, which, if allowed to grow, can significantly reduce soil moisture. Unfortunately, each tillage further reduces roughness, buries or destroys residue and increases the dustiness of the surface layer. By autumn, erosion potential is at a maximum, at the same time as the occurrence of weather patterns which produce highly erosive winds from the SW.

Fields are seeded in late August to early September using deep-furrow drills which place the seed into the moisture zone some 150 mm below the dust mulch. This process, although effective for germinating the seed, destroys all remaining residue and ridges up the dust. By early September of each year, approximately one-half of the Columbia Plateau dry land fields have been recently seeded, are devoid of vegetation and contain significant amounts of loose dust on the surface. Autumn wind storms occasionally produce near-black-out conditions as this surface dust becomes mobilized, creating road hazards and high dust concentrations many miles downwind.

PROCEDURES

In an effort to understand relations between wind erosion, agriculture, climate and air quality, the USDA/ARS and associated university scientists have initiated an integrated research plan to quantify these parameters. Two intensively instrumented wind erosion sites (WES) located on different soil types in eastern Washington provided initial data during autumn 1993. Both WES produced simultaneous wind erosion data and PM_{10} emissions within eroding agricultural fields for a total of 11 erosion events. Table I contains erosion and PM_{10} data for all events from the 1993 field season.

These field sites were located on large (1·6 × 1 km) fallow fields from which simultaneous meteorological, soil erosion and PM_{10} emission data were collected. Meterorological data included wind speed at four heights (0·25, 0·5, 1·0 and 2·0 m), wind direction, ambient air temperature and humidity, soil temperature, precipitation, and total and net radiation. Soil erosion data were obtained using 75 BSNE collectors (Fryrear, 1986) mounted five to a pole (0·1, 0·2, 0·5, 1·0 and 1·5 m), called a cluster. Twelve clusters were placed across a 36 × 55 m rectangular grid with three additional clusters extending for 300 m in the upwind direction (Figure 3). PM_{10} emissions were measured using two high volume (design flow rate of 1132 l m^{-1}) and two low volume (design flow rate of 5 l m^{-1}), mechanically aspirated air samplers. High volume samplers were EPA approved, opposed-jet inertial separation samplers manufactured by General Metal Works*. Low volume samplers were impact separation samplers manufactured by AIRMETRICS*. Inlet heights for the high volume samplers were 1·5 m, and 1·5 and 3·0 m for the low volume samplers.

Both measured soil erosion and PM_{10} emissions were considered to originate from within these fallow fields. However, during high erosive wind conditions, some dust and soil was observed to move freely from field to field and across roads. The effect of transported soil and/or dust on the sampling procedure has not been determined but the possibility exists that during the most intense wind events, measurements

* Use of commercial names is for scientific documentation only and implies no endorsement.

Table I. Soil erosion and PM_{10} data from the Columbia Plateau, Washington, for wind erosion sites 1 and 2. Data are for 1993 erosion events collected using three types of samplers: BSNEs, and two types of mechanically aspirated samplers

Date (day/month)	Event time (h)	2·0 m wind ($m\,s^{-1}$)	BSNE mass (g)	PM_{10} hi-vol no. 1		PM_{10} hi-vol no. 2		PM_{10} lo-vol	
				Mass (g)	Conc. ($\mu g\,m^{-3}$)	Mass (g)	Conc. ($\mu g\,m^{-3}$)	Mass (μg)	Conc. ($\mu g\,m^{-3}$)
Wind erosion site 1: 1·5 m data									
25/8	11·7	7·2	1·3	0·6	806				
11/9	11·8	8·4	16·1	8·7	10875	8·8	12555	48·5	14018
16/9	0·8	6·5	0·1	0·0	160	0·0	89	0·6	2709
8/10	7·0	6·9	0·5	0·3	587	0·3	702	0·8	372
23/10	5·9	6·6	0·1	0·0	70	0·0	82	2·5	1453
3/11	14·6	8·3	0·7	0·7	666	0·5	536	3·9	920
15/11	13·7	8·0	0·5	0·5	516	0·4	456	1·2	305
22/11	16·6	8·5	0·2	0·1	110	0·1	120	1·1	269
Wind erosion site 2: 1·5 m data									
8/10	8·2		0·2	0·1	300	0·1	300	1·0	720
23/10	4·7	6·9	0·0	0·0	42	0·0	42	0·2	160
3/11	16·5	8·1	0·4					4·7	940
15/11	10·6	7·8	0·1			0·6	600	0·3	130

Wind erosion site 1 and 2: 3·0 m data (PM_{10} lo-vol)

Date (day/month)	Event time (h)	WES 1		WES 2	
		Mass (μg)	Conc. ($\mu g\,m^{-3}$)	Mass (μg)	Conc. ($\mu g\,m^{-3}$)
25/8	11·7				
11/9	11·8	3·0	954		
16/9	0·8	0·2	688		
8/10	7·0	0·7	364	0·6	420
23/10	5·9	0·4	232	0·2	110
3/11	14·6	1·1	584	1·5	300
15/11	13·7	0·3	76	0·2	70
22/11	16·6	0·7	167		

could represent multi-source data. In these cases, it is believed that the in-field source would still provide the highest percentage of eroded soil but that suspended dust may be representative of both out-of-field as well as in-field sources.

Instrument limitations

Horizontal soil erosion was measured using BSNE samplers which are whole-sediment samplers having an efficiency of over 89 per cent for saltation particles (100–300 μm) for wind velocities up to 15·7 $m\,s^{-1}$ (Fryrear *et al.*, 1991; Shao *et al.*, 1993), and is considered as approximately isokinetic. However, trapping efficiency decreases rapidly for very fine silt and clay particles and is only 40 per cent efficient for particles <2 μm (Shao *et al.*, 1993). The design is such that sediment-laden air entering the inlet diffuses through a wedge-shaped tray depositing the heavy particles, while most of the fines are removed through an upper screen. Although the sampler collects a certain amount of fine dust, it primarily measures particles travelling by saltation.

Quantifiable lower and upper limits of measurement on high volume PM_{10} samplers are 5 $\mu g\,m^{-3}$ and 400–1000 $\mu g\,m^{-3}$, respectively (Lodge, 1989) over an inlet flow rate range of 1020 to 1240 $l\,min^{-1}$ ($\pm$10 per cent of design flow rate) at ambient conditions. The upper limit is dependent on actual dust concentrations and a maximum wind speed of $\sim$10 $m\,s^{-1}$ (Tish, pers. comm., 1995). Low volume

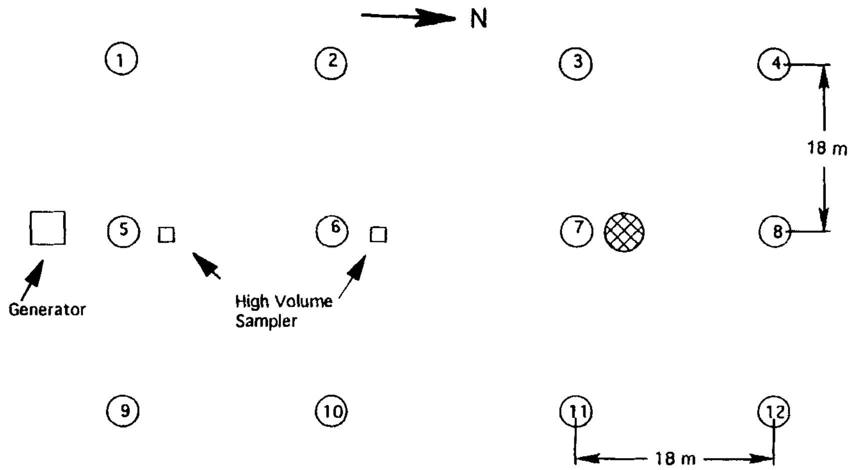

Figure 3. Plan map for wind erosion sites. Circles with numbers are BSNE clusters. Meteorological tower and low volume PM_{10} samplers located at hatched circle. Clusters 13, 14, and 15 not shown

samplers have not been EPA certified. Testing to date indicates that difficulties exist in resolving very low dust concentrations, but the instruments are accurate at higher concentrations up to wind speeds of approximately $13{\cdot}5\,m\,s^{-1}$ (Boyum, pers. comm., 1995). Table I shows that average 2·0 m wind speeds for all events were below the upper wind speed limit for the PM_{10} samplers. However, some of the events contained 2·0 m winds above the upper limit of the high volume samplers for durations of a few to several minutes. In all but one case, these exceedances did not over-saturate the samplers.

During the wind event on 11 September, both high volume filters partially plugged and airflow through the sampler inlets was reduced by ~25 per cent. Subsequent petroscopic examination and size grading of the material on the filters (using a Micrometrics Sedigraph* 5100) showed that approximately 35 per cent of all material was $>PM_{10}$ (Figure 4). As a result, these data were not included in subsequent analyses.

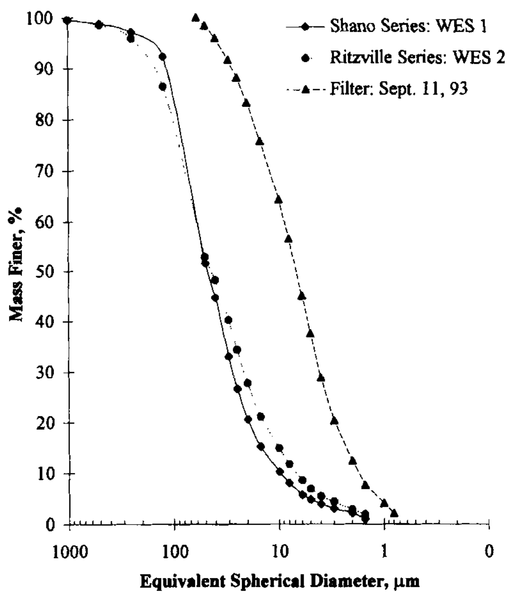

Figure 4. Grain size distributions for soils at both wind erosion sites. Also shown is analysis from high volume PM_{10} filter after wind event on 11 September 1993

SOIL DESCRIPTION

Both wind erosion sites were located on silt loam soils that were developed from loess that contained abundant volcanic ash. Source areas were primarily from glacial flood deposits located in the western part of the Columbia Plateau and the soils generally fine in an E–NE direction. WES 1 was located on a Shano series very fine sand and silt loam soil that contained 52 per cent of the particles $<50\,\mu m$ and 3·9 per cent clay ($<4\,\mu m$). WES 2 was set on a Ritzville series silt loam that contained 53 per cent of the particles $<50\,\mu m$ and 5·4 per cent clay (Figure 4). Primary differences between the two soils are in the coarseness of the sand and in the amount of PM_{10} material which was 10·2 and 14·9 per cent $<PM_{10}$ for WES 1 and 2, respectively. These analyses were made on dispersed samples and, as such, represent a maximum potential for suspendable PM_{10}.

Aggregate size analyses were also performed on both soils from 0–5 and 5–10 cm depths. At both depths, these soil naturally supported ~4 per cent free, loose aggregates $<10\,\mu m$ diameter (Hagen, pers. comm., 1994). For comparison, soils tested from the Great Plains contained less than 0·5 per cent free, loose aggregates $<10\,\mu m$. These data indicate that given erosive wind conditions, these soils have an inherently high potential for emissions of fine dust.

Surface crust and stable soil aggregates (clods) were less likely to form on the Shano soil due to the lower clay content and coarser sand. Additionally, nearly 95 per cent of all Shano soils are irrigated in the immediate area (USDA/SCS, 1967). During the growing season, irrigated soils are usually moist and contain low erosion susceptibility. However, after autumn harvest, these irrigated lands are often bare and dry and are highly susceptible to wind erosion. Conversely, Ritzville soils are located in the dryland region and are entirely dependent upon rainfall for their moisture and are susceptible to erosion during any season. They can, however, form relatively stable crusts after very small amounts (<5 mm) of precipitation.

RESULTS

Horizontal mass flux

Bagnold (1941) and Owen (1964) suggested that a self-regulating mechanism in saltation flux exists close to the surface for both horizontal (f_x) and vertical (f_z) flux regulating particle transport with time. Theoretically, as wind fetch increases from a non-erodible boundary at $x = 0$, f_x increases to the maximum transport capacity, f_{max}, at distance $x = x_f$. Downstream of x_f, f_x remains relatively unchanged as momentum extraction from the wind by the particles already in flow limits additional mass from being entrained. Hence, the resulting flow remains balanced between the rate of particle deposition and erosion, assuming that wind velocity and surface character remain constant.

Requirements of continuity of mass indicate that particle flux in the horizontal direction must be balanced by particle flux in the verticle direction so that the time rate of change in total mass for a given system is a constant. This is expressed mathematically as:

$$f_x \frac{\partial}{\partial_x} + f_z \frac{\partial}{\partial_z} = 0 \tag{1}$$

Stout (1991) used the self-regulating model to derive the solution to Equation 1 for the case where $x_f = f(z)$ only. Boundary conditions stipulated that sediment flux was zero at the field edge, or $f_x = 0$ at $x = 0$. Then as $x \to \infty$, f_x approached f_{max}, although in reality, both x_f and f_{max} vary depending on wind speed and surface characteristics. This simple approach, however, ignored surface variations so that horizontal flux was derived as a function of z only and was expressed as:

$$f_x = f_{max}(1 - e^{-x/x_f}) \tag{2}$$

Equation 2 was fitted to horizontal flux data from two erosion events from WES 1 (Figure 5). An 8 m wide paved road at the upwind edge of the field defined the boundary at $x = 0$. Results are shown in Table II and indicate the downstream distance where, in theory, horizontal flux should reach maximum transport capacity. For both event dates, calculated f_{max} decreased and x_f increased with height. This suggests that,

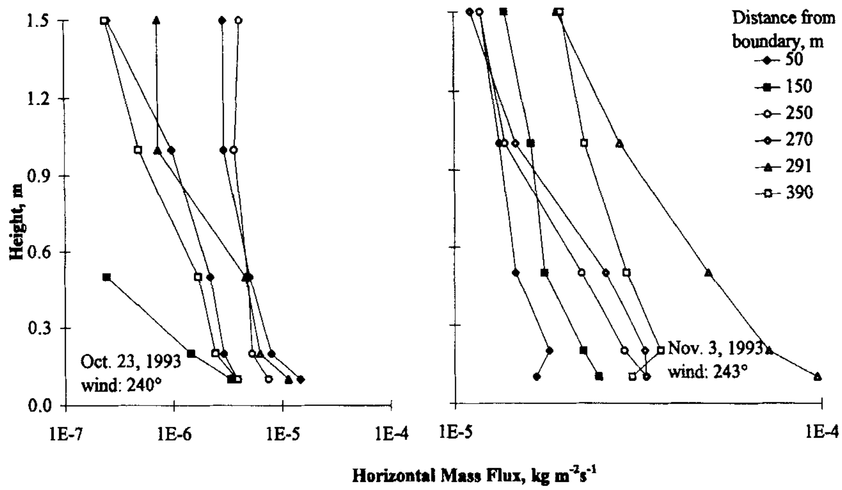

Figure 5. Horizontal mass flux profiles for soil collected in BSNE clusters during two wind events

as observed by Chepil (1946, 1965), mass flux should attain larger values closer to the surface and increase to the maximum transport capacity as a function of distance from the boundary.

Vertical (PM_{10}) mass flux

The concentration of suspended dust, expressed as weight per unit volume of air, was determined from particle mass obtained with PM_{10} samplers using:

$$c = \frac{W_f}{Rt} \tag{3}$$

where c = suspended dust concentration ($\mu g\, m^{-3}$); W_f = weight of particle mass captured on sampler filter (μg); R = flow rate through sampler inlet ($m^3\, s^{-1}$); t = duration of sampling period (s).

Gillette (1977) and Gillette and Passi (1988) related particle concentrations at two heights to the vertical flux of momentum and determined that vertical dust flux could be calculated using:

$$F = C_D u_1^2 \left(-\frac{c_2 - c_1}{u_2 - u_1} \right) \tag{4}$$

where C_D = drag coefficient defined by $(u_*/u)^2$ (Priestly, 1959) where u_* was determined using the logarithmic wind profile equation:

$$\frac{u}{u_*} = \frac{1}{k} \ln \left(\frac{z}{z_o} \right) \tag{5}$$

Table II. Downstream distances at which maximum horizontal flux reached at each height. Assumes that at $x = 0, f_x = 0$

Date	Height (m)	x_f (m)	f_{max} ($kg\, m^{-2}\, s^{-1}$)
	0·1	101·9	9·1E-6
23 Oct 93	0·5	120·0	3·9E-6
	1·5	123·4	1·8E-6
	0·1	150·1	5·4E-5
3 Nov 93	0·5	156·7	3·7E-5
	1·5	34·0	1·5E-5

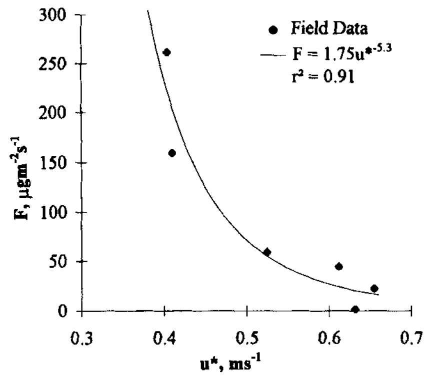

Figure 6. Vertical dust flux as a function of shear velocity. Flux rates determined from suspended dust gradients shown in Figure 7. All data were generated during natural wind events

where u is the measured wind velocity at height z, z_0 is aerodynamic roughness and k is von Karman's constant (0·4); u_1, u_2 = mean wind velocities at two heights (m s^{-1}); c_1, c_2 = suspended dust concentrations at two heights.

Vertical dust flux from fields on the Columbia Plateau show an inverse relation to u_* (Figure 6). This inverse relation is also shown in Figure 7 where suspended dust concentrations at 1·5 m increased as u_* decreased. At 3·0 m, however, suspended dust concentrations appeared to approach a more uniform value, apparently becoming distinct from u_*.

DISCUSSION

There have been numerous studies over the past half-century addressing sand and/or soil erosion and transport mechanics for environments ranging from deserts to farmed lands, e.g. Bagnold (1941) and Chepil (1946, 1965). These studies have looked largely at saltation and, to a lesser extent, creep transport. Only relatively recently have studies begun to address suspension transport, e.g. Gillette (1977), Gillette and Passi (1988), and Nickling and Gilles (1989). Our study differs from previous experiments in that to our knowledge, this is the first study that has collected and reported simultaneous soil erosion and PM_{10} emission data from fine-grained agricultural soils under natural wind conditions. This is an important distinction in that there are no directly comparable data for dust emissions under natural winds in the literature. This discussion will focus first on horizontal soil erosion then vertical dust flux.

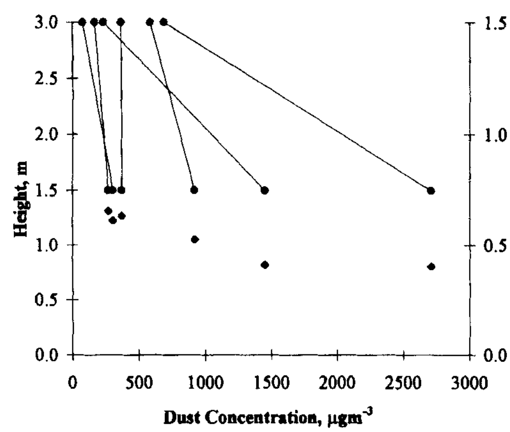

Figure 7. Suspended dust concentrations from low volume PM_{10} samplers. Shear velocities for each wind event are plotted against the 1·5 m dust concentrations

Horizontal soil erosion

Chepil (1965) summarized soil erosion data from agricultural fields in the form of a wind erosion equation:

$$\boldsymbol{E} = f(\boldsymbol{I}, \boldsymbol{C}, \boldsymbol{K}, \boldsymbol{L}, \boldsymbol{V}) \tag{6}$$

in which $\boldsymbol{E}$, the potential average annual soil loss, is a function of $\boldsymbol{I}$, soil erodibility; $\boldsymbol{C}$, the climatic factor for the region; $\boldsymbol{K}$, surface roughness factor; $\boldsymbol{L}$, unsheltered field length in the upwind direction; and $\boldsymbol{V}$, equivalent vegetative cover. Equation 6 '... estimates (a) the potential wind erosion on any field under any climate, and (b) the surface roughness, soil clodiness, vegetative cover, barriers, or width and orientation of field necessary to reduce the potential erosion to insignificance' (Chepil, 1965, p. 130). Subsequently, this equation has been widely used in the U.S. and, to a lesser extent, world-wide to estimate soil erosion losses from agricultural fields. Recently, cases where soil erosion losses have been either over- or under-estimated using the wind erosion equation have promoted a review of its universal applicability. Soils on the Columbia Plateau, in general, do not erode at rates suggested by Equation 6. Two primary reasons for this are (1) most of the soils on the Plateau are very fine-grained and do not behave as the more sandy or heavy clay soils tested in the development of Equation 6; and (2) $\boldsymbol{E}$ is assumed to be applied to soils and fields that contain distinct, non-eroding boundaries so that at the upwind field edge, the transport rate initially builds from zero.

Figure 5 shows horizontal soil flux profiles for two erosion events. In general, these profiles show an increasing transport rate with fetch length, particularly at heights less than 1·0 m and in high wind speed events (Figure 5B). However, the transport rates rarely show continual downwind increases but have been observed to decrease and increase over distances of a few to tens of metres. Therefore, disparities exist between field and calculated horizontal flux rates. The two most probable explanations for these disparities are as follows. First, the solution to Equation 2 assumes that at the field boundary, $f_x = 0$ and builds continually in the downstream direction, thus limiting its use to transport close to the surface. This is consistent with the results from Chepil's (1965) work. He stated that soil erosion due to saltation is zero at the leading edge of a field (non-erodible boundary) and after 10 to 500 m reaches the maximum transport rate for that particular wind. Additionally, he concluded that the maximum transport rate is similar for all soils and is nearly equal to that of dune sand. Hence, it is apparent that differences in the transport rate for the same soil and field are a reflection of changes in the speed and duration of the eroding wind. Stout (1991) evaluated erosion data from the surface to 1·0 m. In this study, data were evaluated from the surface to 1·5 m. Moreover, given textural differences between soils tested in Texas (sand) and those found on the Columbia Plateau (silt loam), the probability that fine-grained material from eroding fields upwind were carried across the boundary was higher on the Columbia Plateau, so it is possible that at some height, say 1·0 m, f_x was not zero. This effect should become more pronounced as wind speed increases, which will also vary the height of non-zero transport. Second, meteorological data were recorded 270 m downwind of the field edge and the probability that natural fluctuations in wind speed would have occurred within this distance, causing deposition and erosion of material, was high, particularly for the rough surfaces tested. Thus, it would have been unlikely that the near-surface transport rate remained constant across these large fields but instead fluctuated with wind strength.

During the 23 October event (Figure 5A), soil flux appeared to have been continually changing across the 340 m width of the test array, particularly at heights below 1·0 m. During the 3 November event (Figure 5B), flux profiles were nearly in equilibrium at heights above 1·0 m, but below 1·0 m (excluding the 291 m cluster) the transport rate increased continually downwind of the field edge. Both data sets show that the maximum near-surface transport rate was not achieved at the indicated distances (Table II). Equation 2 predicted that the near-surface flux (0·1 m) should be reached at 102 and 150 m downstream of the boundary (Table II) for each storm, respectively. Two sampler clusters were located within 150 m of the field edge. If this soil were behaving according to Equations 2 and 6, all flux profiles for clusters downwind of 150 m should be in equilibrium. This, however, was not observed and differences can be attributed to the duration and the speed of the eroding wind. The fluctuating nature of the near-surface transport rate during the 23 October event suggests variations in wind speed may have occurred across the field throughout the 6 h event.

Conversely, near-surface transport rates during the 3 November event increase continually across the test array in response to steady and higher wind speeds.

Similarly, transport rates above 1·0 m were predicted to have been in equilibrium by 123 and 34 m downstream of the boundary (Table II) for each storm, respectively. These rates were close to equilibrium conditions but it was unclear whether the profiles built from zero or whether material was transported across the field boundary (as supported by visual evidence). Because saltation rarely occurs above 1·0 m (Chepil, 1965), comparisons between this and Stout's (1991) data would suggest that both Equations 2 and 6, when applied, should be limited to data from below 1·0 m.

Vertical dust flux

Nickling and Gilles (1989) measured vertical dust emissions from agricultural soils using a wind tunnel but did not report the data because of low significance in the correlation to wind shear velocity. They concluded that numerous variables having complex relations would most likely require more sophisticated analyses than using simple bivariate relations. Our study confirms the complexity of agricultural systems and indicates that wind strength, surface roughness, residue content, soil moisture and soil texture all have significant effects on both soil erosion and dust emission rates. The limited data set however, precludes more than bivariate statistics for this analysis at this time.

Our data indicate that shear velocity, suspended dust concentrations and vertical emissions are inversely related (Figures 6 and 7), which is not consistent with flux data collected using wind tunnels. There are several probable causes for this inverse relation, all of which are based on the fact that these data were generated (and measured) in an emitting source (large fallow fields) by the natural wind. First, at the emission source, the vertical transportation rate of dust rising from the surface increases with wind speed. Thus, samplers operating at constant flow volume may be 'starved' of material in high winds. Second, dilution of suspended dust occurs simultaneously with the vertical transport rate. This effect could actually produce lower concentrations at the source as wind speed increases, even though there may be increased concentrations in downwind 'deposition' areas. Lastly, it is possible that fines were being depleted from the surface at a faster rate under high wind speeds and concentrations calculated from events of several hours duration may appear to be lower than those obtained during events characterized by lower wind speeds. Moreover, as dust continues to rise from the surface and diffuses, surface shear becomes less and less important and the process becomes increasingly defined by turbulent mixing occurring away from the surface layer. The result is a rapid collapse in suspended dust concentrations as height increases (Figure 7).

Chepil (1965) modelled flux rates as a function of u_*^3. He stated that this relation is good for all three modes of transport: saltation, suspension, or creep. If this one function can correctly model all modes of transport, it implies that a relation must exist between the mass of soil in horizontal transport and the mass of dust in suspension. Data from the 1·5 m BSNE and the 1·5 m dust sampler are plotted together in Figure 8 and show that a significant correlation exists between the two variables. Therefore, if the mass of eroded soil is reduced, a simultaneous reduction in emitted dust should be noted. Furthermore, this reduction in eroded soil can be caused by decreased wind strength and/or storm duration, increased soil moisture, or changes in surface, soil or vegetative conditions. This was generally observed for all data but was enhanced for the case where increased soil moisture held erosion losses to a minimum. Wind events occurring on 11 September and 22 November were comparable in duration and intensity (Table I). However, the first autumn rains fell on the Columbia Plateau the week prior to the 22 November event and fields which received the moisture were sufficiently wetted to prevent high rates of erosion. As a result, both PM_{10} concentrations and soil erosion were greatly diminished during the latter event.

CONCLUSIONS

Simultaneous measurements of eroded soil and suspended dust from agricultural fields under natural wind conditions indicate that numerous and complex relations exist between many parameters. Initial soil erosion data from the Columbia Plateau agree, in general, with previously reported data and show an overall increase in eroded mass as distance from the field boundary increases. These data differ from results using

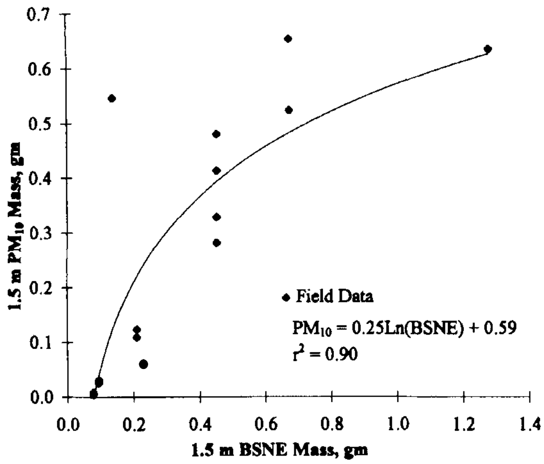

Figure 8. Relation between mass of material collected at a height of 1·5 m using BSNEs and low volume PM_{10} samplers. Data are for all events at both wind erosion sites

mathematical models in that they do not attain maximum transport capacity at indicated distances. This was more pronounced at heights below 1·0 m. Above 1·0 m, suspended dust from upwind sources most likely mixed with in-field emissions. Differences in soil texture and field surface characteristics are primary reasons for the observed differences and indicate that Equations 2 and 6 are not generic and should be applied with caution. Also, when used, they should be limited to near-surface transport.

Additionally, emission rates for fine dust appear to be influenced by many interrelated processes that are based on erosion occurring under natural winds. Near the surface, shear velocity is most important for driving the saltation process, which in turn is responsible for liberating suspended dust through surface impact. Soil texture is again important in that the mass of soil in horizontal (saltation) transport directly affects the mass in vertical (suspension) transport. Changes in surface roughness and residue can affect transport rates over short distances. Further away from the surface, shear forces become increasingly less important and the process becomes dominated by turbulent mixing. This transition between drag- to momentum-dominated transport is marked by a rapid collapse in suspended dust concentrations which approach a more uniform value with height.

Dry land farming is a cropping system highly dependent upon the regional climate and soil quality. Increased losses of fines (by both wind and water erosion) from farmed fields continually degrade the soil quality. As such, growers are increasingly interested in developing farming methods which will maximize their probability for success. These methods include timely, selected tillage operations that promote surface roughness and maximum residue retention, which will reduce both soil erosion and emitted dust.

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